Can baryon stopping explain the breakdown of constituent quark scaling and proposed signals of chiral magnetic waves at RHIC?

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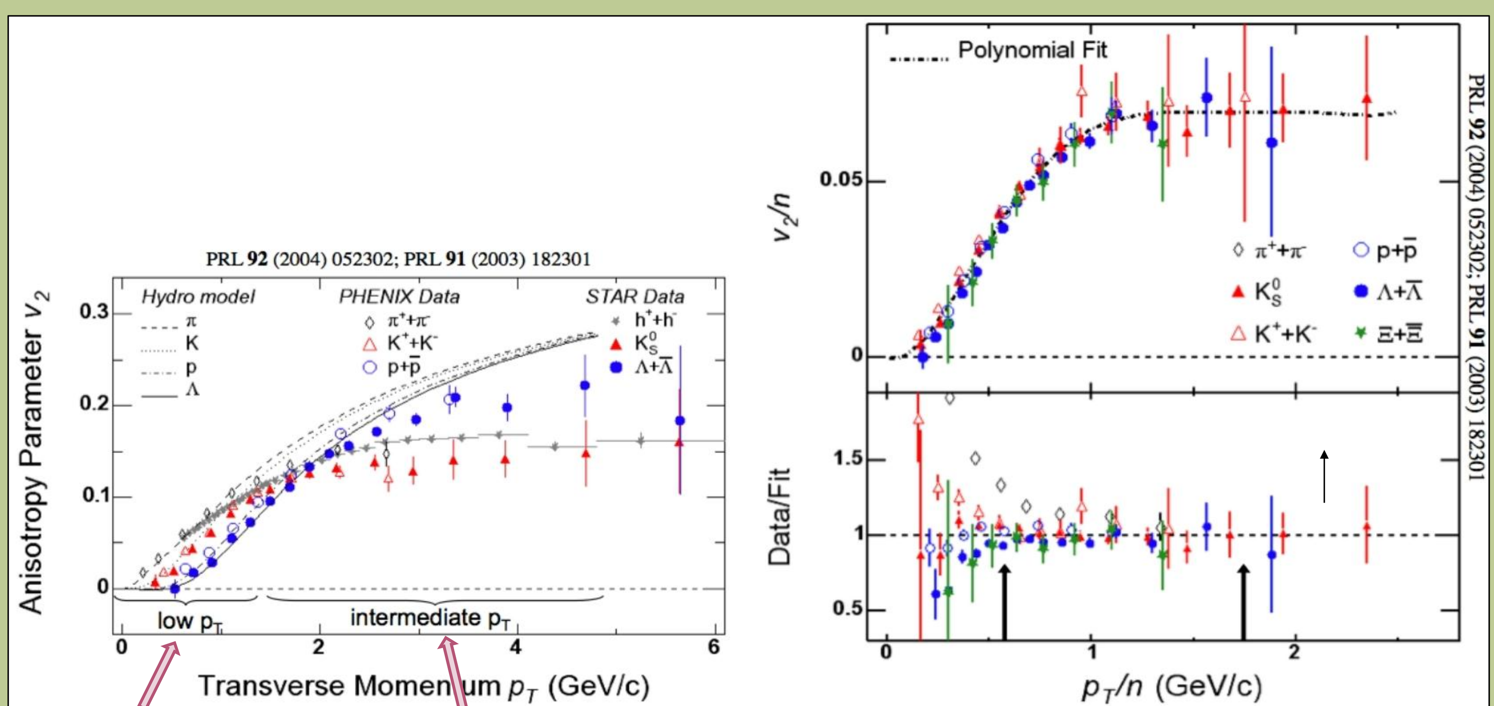
ABSTRACT: Azimuthal emission spectra of various hadron species in ultra-relativistic heavy ion collisions at $\sqrt{S_{NN}} \approx 200\ GeV$ exhibit a curious hierarchy at intermediate p_T ($\approx 2-3\ GeV$). Rather than being ordered by mass, the spectra seem to be ordered by whether the species is a baryon or meson. It is seen that when the elliptic flow v_2 and transverse momentum p_T are both scaled by the number of quarks in each hadron, the spectra fall in line with each other. This number of constituent quark (NCQ) scaling suggests a system where the relevant degrees of freedom are colored partons as opposed to hadrons: the quark-gluon plasma (QGP). Thus, a break down of this scaling as beam energy is reduced could be indicative of the QGP threshold. However, at lower energies, there is also an increase in the number of entrance-channel partons transported to mid-rapidity due to baryon stopping, which can also violate NCQ scaling, even above the QGP threshold. We describe a specific pattern for the break down of the scaling that includes the observed difference in elliptic flow for positive and negative pions.

We also contrast baryon stopping with the Chiral Magnetic Effect (CME)--an alternative model for π^+/π^- flow difference--and discuss results from tests that can distinguish between them.

Number of Constituent Quark Scaling (NCQ)



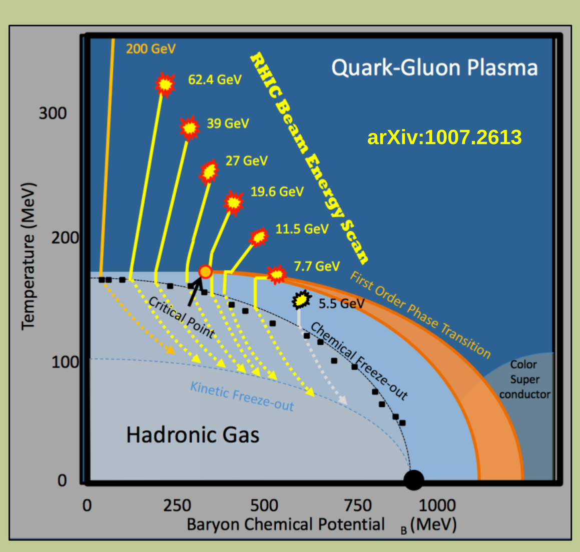
Low p_T: Ordered by mass, consistent with Hydro

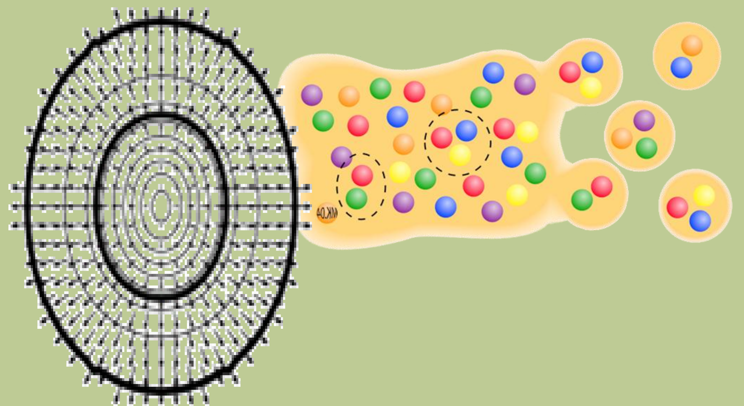
Intermediate p_T: Ordered by baryon/meson

Scale each by *Number of Constituent Quarks* n, and the curves all line up!

The "NCQ" scaling pattern of hadron v_2 at RHIC indicates flowing "quarks," which then coalesce.

This Should break down at low $\sqrt{s_{NN}}$ if quarks are no longer dynamical degrees of freedom.





6.41 GeV

hadron	yield	u	d	s	$\bar{u}$	$\bar{d}$	$\bar{s}$
π^+	72.9	72.9				72.9	
π^-	84.8		84.8		84.8		
π^0 (*)	78.85	39.43	39.43		39.43	39.43	
ϕ	1.17			1.17			1.17
K^+	16.4	16.4					16.4
K^-	5.58			5.58	5.58		
K^0 (*)	10.99		10.99				13.84
$\bar{K}^0$ (*)	10.99			10.99		10.99	
p	46.1	92.2	46.1				
n (*)	70.84	70.84	141.68				
Λ	13.4	13.4	13.4	13.4			
Ξ^-	0.93		0.93	1.86			
$\bar{p}$	0.06				0.12	0.06	
$\bar{n}$ (*)	0.04				0.04	0.08	
$\bar{\Lambda}$	0.1				0.1	0.1	0.1
Sum		305.17	337.33	33	130.07	123.56	28.66

8.86 GeV

hadron	yield	u	d	s	$\bar{u}$	$\bar{d}$	$\bar{s}$
π^+	96.6	96.6				96.6	
π^-	106.1		106.1		106.1		
π^0 (*)	101.35	50.68	50.68		50.68	50.68	
ϕ	1.16			1.16			1.16
K^+	20.1	20.1					20.1
K^-	7.58			7.58	7.58		
K^0 (*)	13.84		13.84				13.84
$\bar{K}^0$ (*)	13.84			13.84		13.84	
p	41.3	82.6	41.3				
n (*)	63.5	63.5	127				
d	1.02	3.06	3.06	3.06			
Λ	14.6	14.6	14.6	14.6			
Ξ^-	1.15		1.15	2.3			
$\bar{p}$	0.32				0.64	0.32	
$\bar{n}$ (*)	0.21				0.21	0.42	
$\bar{\Lambda}$	0.33				0.33	0.33	0.33
$\bar{\Xi}^+$	0.07					0.07	0.14
Sum		331.14	357.73	39.48	165.54	162.26	35.57

Midrapidity yields of common particles from central Pb+Pb collisions measured by the NA49/SPS Collaboration

arXiv:1107.3078v2

Baryon Stopping is important!

$\sqrt{S_{NN}}$	X_{u^T}	X_{d^T}
6.41 GeV	0.57	0.63
8.86 GeV	0.50	0.55

At BES energies, ~50% of quarks are transported from the entrance channel!

What does MCC predict?

- Hadron v_2 has two components: $v_2{}^T$ from *transported* quarks and $v_2{}^P$ from *produced* quarks. In pions, for example:

$$v_2{}^{\pi^-} = X_{d^T} v_2{}^T + (1 - X_{d^T})\, v_2{}^P$$
$$v_2{}^{\pi^+} = X_{u^T} v_2{}^T + (1 - X_{u^T})\, v_2{}^P$$

$$\Delta v_2{}^\pi \equiv v_2{}^{\pi^-} - v_2{}^{\pi^+} = \underbrace{(v_2{}^T - v_2{}^P)}_{\text{positive in MCC scenario}} (X_{d^T} - X_{u^T})$$

What does CMW predict?

- Negative particles get a v_2 boost: $v_2{}^- > v_2{}^+$, regardless of species

$$\Delta v_2{}^\pi \approx \underbrace{r}_{r>0} A_\pm$$

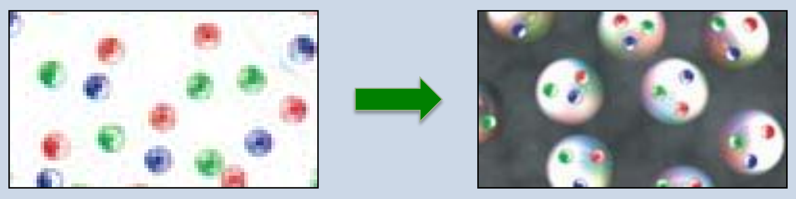
$X_{d^T} \equiv \frac{N_{d^T}}{N_{d^T} + N_{d^P}}$, $X_{u^T} \equiv \frac{N_{u^T}}{N_{u^T} + N_{u^P}}$ Fractions of down (up) quarks transported to midrapidity from the entrance channel

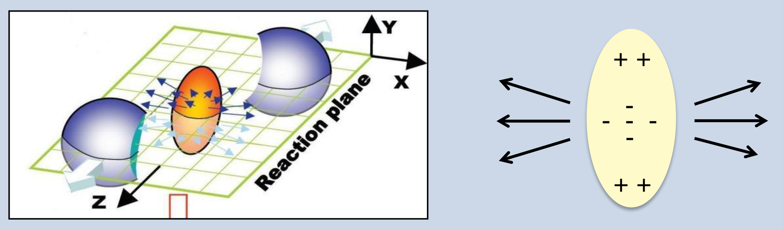
$A_\pm \equiv \frac{N_+ - N_-}{N_+ + N_-}$ Charge Asymmetry

- For pions, CMW and MCC give similar predictions: $v_2{}^{\pi^-} > v_2{}^{\pi^+}$, in agreement with preliminary data
- CMW model goes further: predicts a *positive correlation* between $\Delta v_2{}^\pi$ and $A_\pm$
- MCC model goes further: predicts a *positive correlation* between $\Delta v_2{}^\pi$ and $(X_{d^T} - X_{u^T})$
- To compare the two, we must examine the correlation between $A_\pm$ and $(X_{d^T} - X_{u^T})$

If NCQ breaks down at lower energies, what should we conclude? What changes at lower energies?

- Maybe: Phase transition occurs! – breakdown of NCQ scaling
  - but no specific predictions...

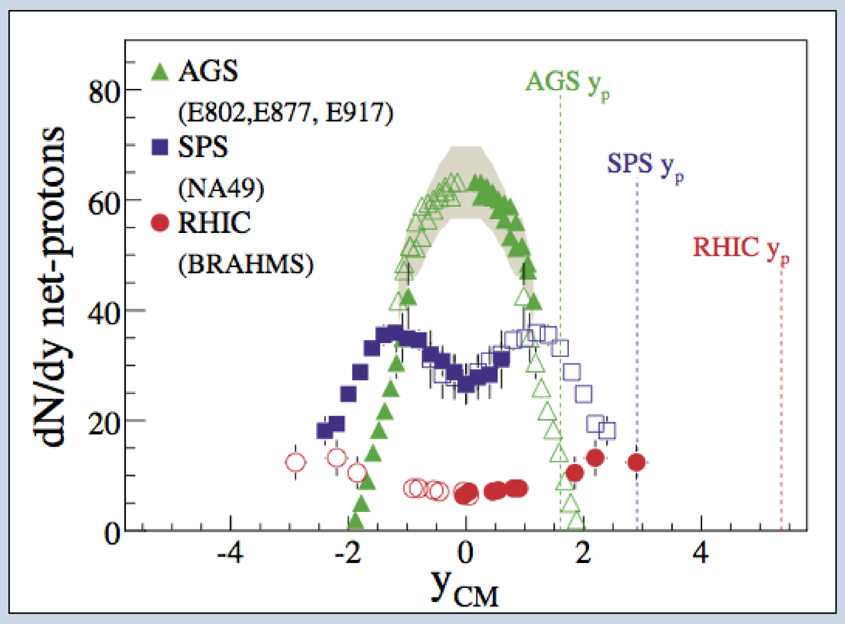




- Maybe: Chiral Magnetic Waves occur!
  - predict v_2 for negative particles always more than for positive particles

Burnier, et al. Phys.Rev.Lett. 107 (2011) 052303

- Certainly: Baryon stopping occurs!
  - **Data**: At BES energies, ~50% of light quarks at midrapidity are transported from the entrance channel
  - what effect could this have...?



- Multi-component coalescence (MCC) model:
  - two populations of quarks with different flows
    - transported (stopped) quarks with $v_2{}^T$
    - produced quarks with $v_2{}^P$
  - $v_2{}^T > v_2{}^P$
  - hadronization by quark coalescence

$$v_2[\pi^+] < v_2[\pi^-]$$
$$v_2[K^+] > v_2[K^-]$$
$$v_2[p] > v_2[\bar{p}]$$
$$v_2[\Lambda] > v_2[\bar{\Lambda}]$$
$$v_2[\bar{\Xi}^+] < v_2[\Xi^-]$$

specific prediction

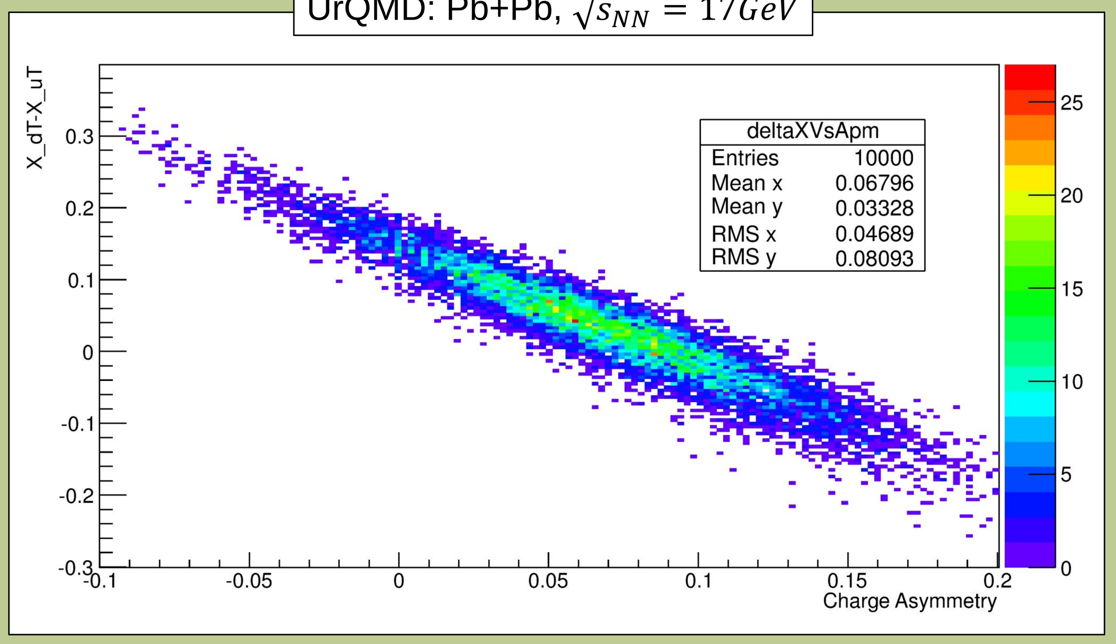
How are $A_\pm$ and $(X_{d^T} - X_{u^T})$ correlated?

Why might it be a *positive* correlation?
- an event with more stopping (but keeping isospin of stopped baryons fixed) INCREASES $A_\pm$ while INCREASING $(X_{d^T} - X_{u^T})$ event-by-event fluctuations of *number* of stopped baryons (isospin fixed)

Why might it be a *negative* correlation?
- keeping the stopping fixed (number of stopped baryons), an event with more stopped protons than neutrons will INCREASE $A_\pm$ while DECREASING $(X_{d^T} - X_{u^T})$ event-by-event fluctuations of *isospin* of stopped baryons (number fixed)

- Surely both fluctuations occur. Which type dominates?

UrQMD: Pb+Pb, $\sqrt{s_{NN}} = 17GeV$



- Simulations show that $A_\pm$ and $(X_{d^T} - X_{u^T})$ have a strong *negative correlation*!
- This means that MCC predicts a *negative correlation* between $\Delta v_2{}^\pi$ and $A_\pm$
- Can check with data!

- Chiral Magnetic Waves and Multi-Component Coalescence are each models that provide and explanation for the breakdown of NCQ scaling *without invoking a phase change.*
- CMW and MCC provide *specific, qualitatively different predictions* for the pattern of NCQ breakdown

CMW predicts:
- $\Delta v_2 > 0$, regardless of species
- $\Delta v_2{}^\pi$ and $A_\pm$ are positively correlated

MCC predicts:
- Species dependence for Δv_2
- $\Delta v_2{}^\pi$ and $A_\pm$ are negatively correlated